Development of Life Cycle Models for Evaluating Novel Aircraft Configurations

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Abstract

The economy's and population's growths in the last years, specially in the developing countries, have been conducing to an increment of the demand for aircraft not only in terms of quantity but also in terms of configuration such as the high *aspect ratio* ones and new materials such as the composites. Although aluminium is currently the most used material in aeronautics, composites start to enter the aviation market due to their great mechanical properties that fulfil in a better way this industry requirements. The main objective of this study is to perform a multidisciplinary analysis of discrete variations in a simplified wing model, provided by the Brazilian company *EMBRAER* on project *NOVEMOR*, in order to obtain the best wing model out of 12 different configurations. Variations in the internal and external geometries and material were performed. The different wing configurations were analysed regarding their aerodynamic performance, structural behaviour and life cycle impacts both in environmental and financial terms for the production, use and *End-of-Life* phases. The final results were provided by the multidisciplinary analysis and the comparison between all the wing configurations was made by the use of an *Analytical Hierarchy Process*. Furthermore, the main cost source was determined and parametric studies were performed in order to get clearer conclusions from this multidisciplinary analysis.
Keywords: High Aspect Ratio Wing, Composite, Multidisciplinary Analysis, Life Cycle Analysis.

1. Introduction

A product such as an aircraft component has a technical life cycle that can be given by a *S-curve*. The product's life cycle follows the four fixed stages birth, growth, maturity and death, like the living organisms [1]. Nowadays, the conventional aircraft designs are in the last step of their *S-curve* [2]. Therefore, the aerospace engineers are trying to develop new aircraft configurations to meet the market's needs. In this study, a novel wing configuration such as a high *AR* concept will be analysed and compared with regular size configurations. An important factor that had a huge contribution for the generation of novel aircraft configurations is the environmental concern. Governments imposed regulations for lower aircraft's emissions. Due to this issue, the engineers need to develop new aircraft configurations or to improve the actual ones in order to obtain a more efficient concept in terms of fuel consumption and emissions [3]. All the stages in an aircraft life are important and need to be well predicted in order to understand the pros and the cons of an investment on a certain model.

1.1. Motivation

In terms of manufacturing and maintenance most of the aircraft structures are known to be built with applications of fibre-reinforced composites. The structures made in composites allow components to have a significant weight reduction, while keeping a high mechanical resistance. Therefore, it is profitable for the aircraft's operators and maintenance team [4]. Regarding the wings' structures, not only the material but also the external shape and the internal composition affect the whole aircraft performance.

1.2. Global Market Forecast

The aeronautical industry has not stop growing since it was created. The estimation related to the manufacturers indicates that by the year 2035 they will have a total deliver of 2,110 freight and 33,710 passenger aircraft. The passenger fleet will be more than doubled from 2016 to 2035. According to the Airbus *Global Market Forecast* there will be a total of 33,070 new aircraft deliveries by the year 2035, in a market value of $5.2 trillion [5]. Novel aircraft configurations can play a crucial role in terms of fulfilling airlines with more fuel efficient models. The continuous growth of the fuels' prices needs to be fought not only with the improvement of the existing technologies, but also with the implementation of new ones.

1.3. Novel Aircraft Configurations

In order to improve the aircraft operational and maintenance costs, engineers need to develop novel aircraft concepts that can be more or less disruptive. Unconventional aircraft configurations start to appear not only in the military, but also in the commercial market. In this study, the unconventional aircraft configuration analysed is a conceptual wing with a high *AR*. Furthermore, due to the airports' restrictions regarding the aircraft's size and the higher probability of having dynamic aeroelastic phenomena such as *flutter* [6], it can be considered unconventional at some level. Despite the predicted lower structural performance, the introduction of a high *AR* wing on an aircraft will raise the value of the configuration's lift over drag ratio ($\frac{L}{D}$), decreasing, consequently, the block of fuel consumed by the aircraft in each flight. Therefore, in the use phase of the aircraft's life cycle, the costs and the environmental impacts will be much lower.

1.4. Process-Based Models - PBM

Although conventional and unconventional aircrafts have particular pros and cons that are easily inferred, others need to be explored. A useful tool to perform that analysis is the *PBM*. A *PBM* starts by the process model, in which the process requirements and the boundaries are established after knowing the product's description. Afterwards, knowing the operation conditions imposed for the processing requirements, in the operations model, the resources consumption is established in order to have the global inventory analysis of the model. With that inventory, both financial and environmental models may be performed by having the costs and the environmental factors, respectively.

1.5. Objectives

The main goal of this study was to perform discrete changes on the initial wing concept [7] provided by the Brazilian company *EMBRAER* for project *NOVEMOR* and to get insights from different disciplines (aerodynamics, structures, costs and environmental impacts).

The first step was to create 11 different wing configurations by performing simple changes on the original wing model. This initial model had an *aspect ratio* of 7.8 and it had no ribs (internal reinforcing structures). The 12 different case studies came out from 3 distinct manufacturing processes, 2 variations of external wing geometries and 2 internal wing configurations. Although the airfoils used for both wings are the same, the chord is smaller and the span is bigger for the second wing, since the wing area was the same for both external configurations. In figure 1 are represented the paths of the 12 case studies tested in this study.

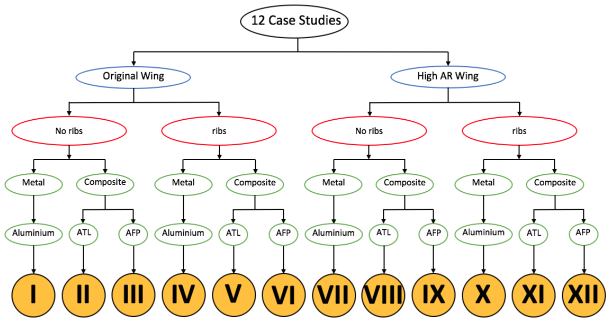


Figure 1: The 12 case studies analysed in this multidisciplinary evaluation

The methodology followed was to perform 3 distinct analyses on the 12 different wings (original wing and the other 11 concepts). The analyses performed on the wings were *Aerodynamic*, *Structural* and *Economic and Environmental evaluations*. After the analyses were performed and the results obtained and interpreted, they were balanced in an *Analytical Hierarchy Process* (*AHP*) in order to get the best wing out of the 12 studied.

In order to attain the aim of this study, the question to be formulated was:

"What are the decisive variations on an initial optimized wing concept that can produce an even better structural and aerodynamic configuration without increasing significantly the costs and the environmental impacts?"

2. Background

2.1. Process-Based Cost Models - PBCM

The objective of the *PBCM* is to establish the path to follow between the product description and its final cost in order to optimize the operations in all its phases. The importance of establishing a *PBCM* is to have the necessary information to make the key decisions before the operations start to take place, regarding all the technological alternatives. In figure 2 are shown the stages of a *PBCM* [8].

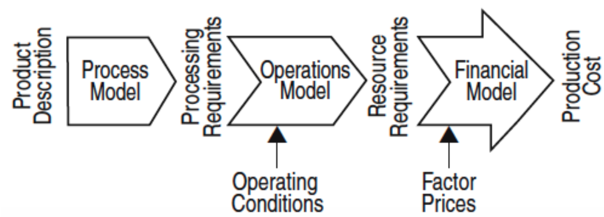


Figure 2: Stages of a technical cost model [8]

Time is always a big significant constraint to the model, not only because more resources are needed in order to raise the daily production, but also because it defines the capital requirements. In figure 3 are shown the parts that build a line utilization during a day.

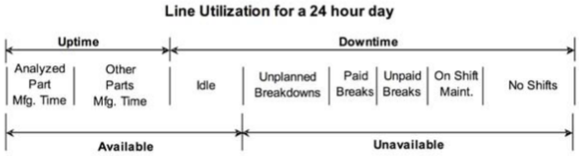


Figure 3: Composition of a line utilization in a 24 hour day [8]

2.2. Life Cycle Analyses

Nowadays it is very important to determine a product's impacts not only in the economical field, but also in its environmental consequences in its complete life cycle. Therefore, the resources of a part's production, use and *EOL* may be used to determine its *LCC* and *LCA*.

In order to determine the costs of the global product's life cycle, the method used is the *LCC*. Variables such as the concept's design or material have direct influence in all the product's life cycle phases. The acquisition costs are most of the times used as unique and principal conditions for decision making on equipments' investment [9]. In the *LCC* method, the production costs, the costs during the product's useful life and the costs for its final disposal are determined and a long time decision can be justified [9]. This evaluation is suitable to compare between different products for the same application in terms of their total expenses, contributing with the possibility of easily identifying the main costs' source in each life cycle phase [9].

LCA is a methodology to evaluate and comprehend the environmental issues of a concept's manufacture and activity. All this analysis performed by the *LCA* is made along the product's life cycle [10]. In this way, *LCA* processes are considered as a 'crandle to grave' description of the environmental issues of a product's generation [11]. Two significant resources that the *LCA* takes into account in its process description are the energy and the materials involved in the production. These four steps must be followed in order to get a full *LCA* analysis [10]:

- Project the *LCA* process always with the main goal in mind and the scope well defined;
- Develop an inventory analysis to determine the process' material and energy flows;
- Establish the *Life Cycle Impact Assessment* (*LCIA*) in order to evaluate the environmental impacts of the whole process;
- Finish the process with an improvement assessment and result's interpretation to help to take certain decisions that will reduce the environmental impact and search for less pollutant alternatives.

2.3. Production Processes

There is a wide set of composite's production techniques and systems possible to use in the automatic manufacturing of components for the aeronautic industry. Before the composite's automated manufacturing, the most common method used was the *hand-layup*. *Hand Lay-up* is a traditional open moulding method in which the production volume per mould is very low. Due to the market's demand, the manual methods needed to be faster and to have a larger daily production. With this, emerged the need of developing automated manufacturing processes [12]. From all the processes used in the composite part's production the *ATL* and the *AFP*, which belong to the automatic lamination machine's group, will be the ones analysed further on. These models are capable of producing advanced composites, which have even greater mechanical properties than the common composites [13]. Actual aircraft concepts have more than 50% of their total weight made of advanced composites. The main property of the advanced composites that mostly contributed for their spread into other engineering environments is their cost effectiveness. The *AFP* process has great similarities with the *ATL* one, but uses a set of finite *prepreg* slices that are placed on the head and then deposited simultaneously [13].

Regarding the metal's production processes, machining (milling) is one of the most used in the aeronautic industry. Aluminium is a crucial material in the aerospace industry because it is very easy to manipulate. Before the machining process is initiated, the raw material needs to be placed in a *JIG* [14]. The *JIG* tool increases the production because stages such as part's set-up and check are expendable. Therefore, costs coming from quality checking no longer exist [15].

3. Implementation

All the concepts generated will be analysed in terms of aerodynamics, structural behaviour, costs and environmental impact of their production, use and *EOL*. In order to achieve the best wing model out from a discrete analysis, the first step was to generate 11 different models from the original one provided by *EMBRAER* in project *NOVEMOR*. Afterwards, those 12 wing configurations (the original wing and the generated concepts) were submitted to

4 distinct analyses: *Aerodynamic*, *Structural*, *Economic* and *Environmental*, during their complete life cycle.

3.1. Models

The original model was developed by the Brazilian aircraft manufacturer *EMBRAER* in the scope of the *EU FP7 project NOVEMOR*. Beyond the already optimized airfoil along the wing span, the structural model was composed by: wing skin and front and rear spars, forming a wing-box. The simplified wing model has an aspect-ratio of 7.8 ($AR = 7.8$) and no ribs. Therefore, other concepts were developed from this one, with the introduction of 10 ribs as it is possible to view in figure 4.

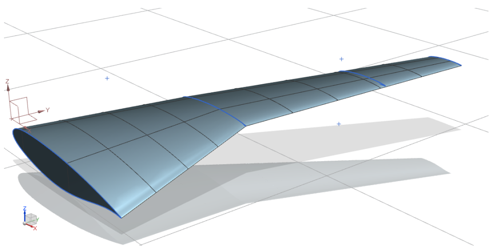


Figure 4: Original configuration with the introduction of 10 ribs parallel to the xz plane

In this way, four different configurations were established in order to be analysed further on:

- Wing 1 without ribs: original simplified wing-box layout;
- Wing 1 with ribs: original wing with the introduction of 10 ribs and with $AR = 7.8$ (original value);
- Wing 2 without ribs: concept similar to the original one, but with $AR = 16.0$ (higher value);
- Wing 2 with ribs: wing with the 10 ribs and with $AR = 16.0$ (higher value).

For these 4 different concepts, two types of material where applied, giving a total of 8 distinct models to analyse, with the same thickness for all the wing components:

- aluminium $A6061$;
- composite with carbon fibres $IM7$ and epoxy resin, with a final stacking sequence of $[[-45/0/45/90]_S]_7$.

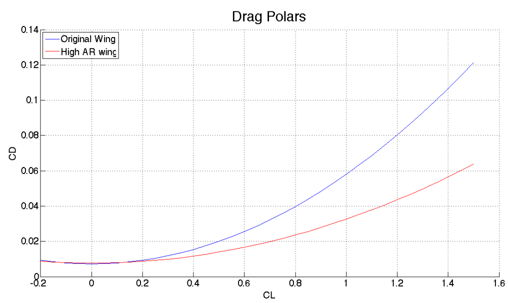
3.2. Aerodynamic Methodology

Since the existence of ribs as intern structural components of the wing does not affect the aerodynamic analysis, the external geometry will be the only variable in this comparison. For a better comparison between these two configurations, flight parameters such as altitude ($h_{cr} = 38,000\ m$) and speed ($M_{cr} = 0.78$) must be the same. The methodology followed in this section is the one described by *Corke* in his textbook [16], in chapter 4 (*Main Wing Design*).

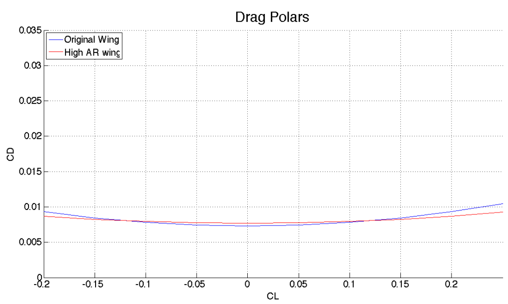
The drag polars (i.e. the drag coefficient C_D as a function of the lift coefficient C_L) for the original concept and for the high AR one are, respectively, presented in equation 1.

$$\begin{cases} C_{D_{wing1}} = 0.00730 + 0.0507 \cdot C_L^2 \\ C_{D_{wing2}} = 0.00769 + 0.0249 \cdot C_L^2 \end{cases} \quad (1)$$

In figure 5 it is possible to note that in the wing with lower AR (the original one) the drag coefficient increases more with the lift coefficient in comparison with the high AR configuration. Also, figure 5(b) shows that for very low lift coefficients the original wing produces less drag than the high AR wing. This happens because, maintaining the wing area, an increase of the aspect ratio will decrease the chord. A reduction in the chord length decreases the *Reynolds Number* which causes a higher aerodynamic viscous resistance. However, this phenomena dissipates with the increase of C_L, where the decrease of the induced drag (on the high AR wing) is higher than the increase of the viscous resistance.



(a) Drag Polars



(b) Drag Polar's zoom for low values of C_L

Figure 5: Drag Polar for both external wing configurations

The lift polars for both wings are shown in equation 2 and represented in figure 6.

$$\begin{cases} C_{L_{wing1}} = 0.2131268 + 5.94 \cdot \alpha \\ C_{L_{wing2}} = 0.2131268 + 7.02 \cdot \alpha \end{cases} \tag{2}$$

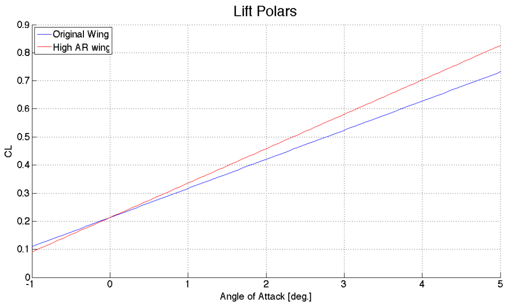


Figure 6: Lift Polar for both external wing configurations

In order to determine the moment coefficient, C_M, for both configurations, some assumptions were made regarding the gravity centre and aerodynamic centre positions, respectively $x_{ac} = \frac{\bar{c}}{4}$ and $x_{CG} = \frac{x_{ac}}{4}$, on each wing in order to have the system at a very stable stage. The most important value to analyse is the $\frac{L}{D}$ ratio. In a cruise out to destination level, the fuel weight fraction between the beginning and the end of this phase will be directly related to the $\frac{L}{D}$ ratio in the *Breguet* range equation shown in expression 3.

$$R = \frac{V_{cr}}{C_{TSFC}} \cdot \frac{L}{D} \cdot \ln\left[\frac{W_i}{W_f}\right] \tag{3}$$

By checking the *Breguet* range equation 3 is possible to understand that, for the same range R, the same cruise speed V_{cr} and thrust-specific fuel consumption C_{TSFC}, a higher $\frac{L}{D}$ value induces a lower $\frac{W_i}{W_f}$ value, so for the same initial fuel weight W_i, the fuel weight at the end of the cruise phase W_f will be higher, so the block of fuel used will not be so higher as it would be for lower $\frac{L}{D}$ values. The influence of the $\frac{L}{D}$ ratio in the fuel consumption will also affect not only the concept's *LCC* but also its *LCA*, as it will be analysed in the next sections.

3.3. Structural Methodology

The Finite Element (*FE*) *software* used to perform the structural analysis was *Siemens NX*. The mesh refinement had different criteria for the 2 materials used. For the configurations made in aluminium, the criteria adopted was the *von Mises* stress. This criteria is one of the most commonly used to refine the geometry's mesh, when it is made in metal [17]. For the configurations made in composite the criteria adopted for the mesh refinement was the deformation energy's density, since it analyses the whole composite structure and not each layer individually. The analyses performed regarding the structural domain were *Static Analysis* to get the maximum tip displacement and the maximum stress, *Modal Analysis* to get the first 10 vibration modes and *Linear Buckling Analysis* to determine the first 10 critical loads. The load applied to all the wings in the *Static Analysis* was the same and it behaved like a pressure with a constant distribution along the wing's lower surface and in the positive z direction. The intensity of the load was determined by the ratio $\frac{W}{S}$ of the heaviest configuration and applied as a pressure to all the models.

3.4. Economic & Environmental Evaluation

The first step was to determine the boundaries to apply on the *PBM* in order to perform the *Economic and Environmental Evaluation.* The boundaries of this evaluation were the 3 life cycle phases: *production*, *use* and *EOL*. With the boundaries established, the resources were the *energy*, the *material flow*, the *fuel consumed* and the *material disposal*. Figure 7 shows the resources consumption assumed in each life cycle phase for both financial and environmental models.

Phases	Energy	Material Flow	Fuel	Material Disposal
Production	X	X		
Use			X	
EOL	X			X

Figure 7: Resources Consumed in each Life Cycle Phase

The resources were, further on traduced into costs on the financial model and into environmental impacts on the environmental model. With the scope presented in figure 8 it was possible to establish not only the *LCC*, but also the *LCA* for the distinct wing configurations.

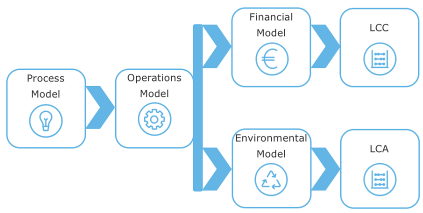


Figure 8: PBM Scope

The production cost model is different for the composite and the aluminium wings. Both composite production models (*ATL* and *AFP*) follow the same stages. The first stage is the reception check and storage. This block aggregates the verification of the material after its arrival at the company and the type of storage required to guarantee that the *prepreg*'s properties are maintained. After that, a second process may start its function. Here, the *prepreg* rolls are prepared and clear for the application of the cooper are glass fibre layers. The third stage, in which the fibre placement happens, is the main difference between these 2 composite *PBM*'s, since its operation requires different machines. Afterwards, the fourth step of the process begins and the glass fibre is applied. After this second application of glass fibre, the part is placed in the autoclave to be cured, on the fifth stage of the model. Step number six of this composite model flowchart is the part's demoulding for final adjustments. The last macro block is when the part goes to the *NDT* (*Non-Destructive Tests*) for the final operations.

In a very similar way as in the composite's *PBCM*, the metal's *PBCM* was performed in a block's diagram sequence with different 7 stages for the part's production in the aluminium. Scrap material will appear in all the macro blocks. In a particular analysis of blocks 2 and 4, respectively, machining and shot peening. The reworking processes are made on the same machine. Therefore, the part will return to the beginning of the same macro block. On the other hand, for macro block 5, surface treatment and painting, the rework is done outside the block, since it is performed in another machine.

For the *LCC*'s production phase and the part's manufacture scope in the *LCA* were used the same resources (*material flow* and *energy*) and the same stages were taken into account. After the part's manufacture was completed, its utilization during its useful life was transformed into environmental impact and finishing at the part's *EOL*. In this way, a whole cradle-to-grave analysis was performed for the different configurations.

In order to determine an approximation of the total costs and environmental impacts of the useful life of the aircraft with the different concepts, it was necessary to determine the fuel consumption for all the flights made. The only flight mode considered was the cruise level and the cruise speed adopted was the one use in the aerodynamic analysis. It had to be assumed the same values for the thrust specific fuel consumption in the cruise level, for the single flight range, for the initial fuel weight, for the total distance travelled in the aircraft's useful life and for the fuel data. The *use* of the different configurations in an aircraft is directly dependent of the $\frac{L}{D}$ factor by the *Breguet's Equation*, in expression 3, so by the aerodynamic analysis there would be only 2 different values for the utilization cost. With the determination of the fuel consumption regarding the useful life of the configurations, it was possible to determine the costs and the environmental impacts of the distinct concepts in this life cycle phase.

For both *LCC* and *LCA* analyses, the same boundaries were applied. On the use phase the blocks of fuel consumed establish the connection between the *LCC* and the *LCA*, enabling the possibility of generating a financial model and an environmental model from the operations model. To transform the resources' consumption into environmental impacts was used, again, the *software SimaPro* through the method *ReCiPe*.

The cost of recycling an aluminium part was assumed to be at about 30% of its production cost [18]. Thus, knowing the production cost of each configuration, it was possible to determine the *EOL* costs for the aluminium wings. The *EOL* alternative used for composite configurations was the incineration. The energy spent on the combustion is insignificant when compared to the energy produced by this process. Therefore, for the composite wings, the *EOL* costs due to incineration were considered null [19]. For both *LCC* and *LCA* analyses, the same boundaries were applied. On the *EOL* phase the energy consumed on the final disposal processes and the parts' material establish the connection between the *LCC* and the *LCA*. Also, in order to transform the resources' consumption into environmental impacts was used the *software SimaPro* through the method *ReCiPe*.

4. Results

4.1. Aerodynamic Analysis

Since the case study had cruise level conditions, a low angle of attack of 0.5 was assumed for both wings. For a better comparison between the two concepts, apart from the parameter C_M, $\frac{L}{D}$ is crucial to get, for this angle of attack. In table 1 are shown these two coefficients for both wing configurations.

Dimension	Original Wing	High AR Wing
C_M	-0.0497	-0.0515
$\frac{L}{D}$	24.39	28.70

Table 1: Moment Coefficient and Lift to Drag ratio

The performance of the wing depends a lot on its $\frac{L}{D}$, as it was possible to understand at the end of section 3.2 with the *Breguet* range expression (see equation 3). An increase of the wing's *aspect ratio* for the same airfoil area provided a decrease on the induced drag. However, the Reynolds number was lower and conduced to higher viscous drag values. For low angles of attack the lift over drag ratio was higher for the wing with higher *aspect ratio.* Taking into account *Breguet's* equation, an aircraft with a higher $\frac{L}{D}$ requires less fuel to fly the same flight ranges, considering the same cruise speed and the same thrust-specific fuel consumption. From figure 9, it is possible to check that the high AR wing had a higher $\frac{L}{D}$ ratio than the original configuration, for a positive α.

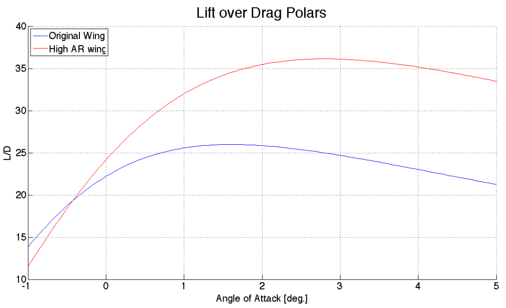


Figure 9: Lift over Drag Polar for both external wing configurations

Flying with a moderate angle of attack, the shock waves' phenomena on the wings increases its intensity, raising the drag load's value and conducing to a lower lift over drag ratio. Since the position of the gravity centre assumed was, for a very stable stage, $x_{CG} = 0.125 \cdot \bar{c}$, a possible increase of α would increase the lift load in the main wing, increasing the lift coefficient and, consequently, decreasing the pitching moment of the aircraft, since it had negative values. However, the original wing had a better value of C_M than the high AR one. The closer this value is to zero, the lower will be the load on the horizontal stabilizer to balance the aircraft [20]. As it was expected, the wings with a higher aspect ratio have bigger values of $\frac{L}{D}$ ratio. The higher this ratio is, the better will be the wing's performance. In this way, for the same root airfoil, high aspect ratio wings conduce to a lower consumption of fuel blocks as it will be possible to check out from *Breguet's equation* in the cost's analysis.

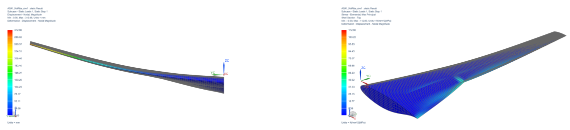
4.2. Structural Results

The results from the *static analysis* analysed in this study were the maximum tip displacement, w_{max}, and the maximum stress on the structure σ_{max} and are presented in figure 10.

Concept	σ_{max} [MPa]	w_{max} [mm]
Wing 1, no ribs, IM7	277.47	553.43
Wing 1, no ribs, A6061	113.97	312.68
Wing 1, ribs, IM7	250.04	547.77
Wing 1, ribs, A6061	101.32	309.58
Wing 2, no ribs, IM7	556.13	4117.14
Wing 2, no ribs, A6061	231.80	2326.93
Wing 2, ribs, IM7	561.75	4096.56
Wing 2, ribs, A6061	232.36	2316.49

Figure 10: Static Analysis

The wings were cantilevered at their roots and an ascendant pressure was applied on their lower surface. In order to check this system's consequence, it was analysed the wing's tip displacement and its maximum stress (check figure 11 for an example, this result belongs to the original wing, without ribs, made of aluminium *A6061*).



(a) w_{max} (b) σ_{max}

Figure 11: *Static Analysis* for the original wing, without ribs, made in aluminium *A6061*

As it is possible to check from figure 10, the first interpretation that these results provide is the fact that, for this loading type and intensity, the composite configurations had higher values of maximum stress and maximum tip displacement. Multiple factors related to the composite structure may be behind this result, such as the layer's orientation, the number of layers or the layer's thickness. From figure 10 it is possible to check that the high aspect ratio wing configurations had bigger values of maximum tip displacement. This happens due to the fact that, for the same wing area and the same load applied, these configurations were longer and narrower. The introduction of ribs in the internal configuration reduced the maximum tip displacement since these components gave an extra resistance to the body. However, the maximum stress on the configurations with ribs was slightly higher because it happened on these structural components.

The results taken from the *modal analysis* were the first 10 vibration modes. One can note that the fundamental natural frequency, corresponding to the first flap bending (out-of-wing plane bending) decreased as the *aspect ratio* increases. The increase of a wing's *aspect ratio*, maintaining the wing area, turned the wing into a narrower and longer configuration. Thus, wings with higher *aspect ratio* tend to look and behave as beams. Wings with lower *aspect ratio* are shorter larger, looking and behaving more as plaques. The *modal analysis* reflected this behaviours.

The *buckling analysis* gave the values of the critical loads to the structure. As well as in the *Modal Analysis*, in the *Linear Buckling Analysis*, there were some modes of the same geometry that reveal a beam critical behaviour and others that reveal a plaque buckling response. The critical loads started, for all the configurations, above 100 kN. Also, the critical loads were lower for the configurations made in the composite *IM7* than for the ones in aluminium *A6061*. Comparing the different AR concepts, the original wings had higher values of buckling loads than the higher AR wings. Also, the introduction of ribs in the structures increased the values of the critical loads.

4.3. Economic & Environmental Evaluation

As figure 7 exposes, for the economic and the environmental evaluation, each life cycle phase has its own resources consumption. The boundaries of these analyses were the 3 life cycle phases: production, use and *EOL*. Figure 12 exposes the final *LCC* results, for the financial model.

Concept	PBCM	Production Cost (euro)	Use Cost (euro)	*EOL* Cost (euro)	Total Cost (euro)
Wing 1, no ribs	Metal	46,489	58,831,300	13,947	58,891,736
	ATL	341,455	58,831,300	0	59,172,755
	AFP	296,769	58,831,300	0	59,128,069
Wing 1, ribs	Metal	50,575	58,831,300	15,173	58,897,048
	ATL	381,534	58,831,300	0	59,212,834
	AFP	331,430	58,831,300	0	59,162,730
Wing 2, no ribs	Metal	46,462	50,270,300	13,939	50,330,701
	ATL	435,617	50,270,300	0	50,705,917
	AFP	309,231	50,270,300	0	50,579,531
Wing 2, ribs	Metal	47,904	50,270,300	14,371	50,332,575
	ATL	453,850	50,270,300	0	50,724,150
	AFP	332,072	50,270,300	0	50,592,372

Figure 12: Total Costs of the different pair of Wing Configurations

From figure 12 it is possible to understand that the metal's manufacturing processes are much cheaper than the composite ones. The composite processes are approximately 8 times more expensive. However, making a distinction in the composites' models, the *AFP* is significantly less expensive than the *ATL* process. The cost per process hour in the *ATL* model was cheaper than in the *AFP* model. The material waste was much more in the *ATL* model. In this way, even with a more expensive stage of fibre placement, the *AFP* model produced cheaper wings due to the lower material waste in the whole manufacturing process. Making a global comparison between the wings, the introduction of ribs increased the production cost, since the quantity of material required is larger. Wings with a higher aspect ratio induce an aircraft to have lower values of blocks of fuel consumed during its useful life, due to a higher $\frac{L}{D}$ ratio. Therefore, these wing configuration's use phase will be less expensive and also less pollutant than the original external configuration wings provided by *EMBRAER* in project *NOVEMOR*. From figure 12 it is possible to check that the life cycle phase that had more impact in the wing configurations' cost was the use phase. From figure 12, the wing with the cheapest life cycle cost was the high aspect ratio wing, without ribs produced in aluminium. On the other hand, the most expensive wing from out the 12 different configurations was the original wing, with ribs, made in composite by *ATL* process.

For the same resources consumption considered as in the financial model, the environmental model for the production phase gave an endpoint analysis, represented in figure 13. From the endpoint analysis of the production phase it is possible to conclude that the introduction of ribs increased the environmental impact since the quantity of material used was higher. Also, composite wings had a much more pollutant production phase than aluminium wings. In the use phase the variable taken into account was only the blocks of fuel consumed during the entire aircraft's useful life. The wings with a higher aspect ratio had higher $\frac{L}{D}$ values and, by the *Breguet's Equation* 3, consumed less fuel in their flights. This fuel consumption impact is expressed in figure 13. Different material parts expect distinct *EOL* scenarios. It was considered that the metal components were recycled and the composite parts were incinerated. As it was expected, the composite wings had much more environmental negative consequences in their *EOL* phase than the aluminium wings.

Concept	Material	Production	Use	*EOL*	Total
Wing 1, no ribs	Metal	3.4	115.0	0.4	118.8
	Composite	4.65	115.0	1.2	120.05
Wing 1, ribs	Metal	3.7	115.0	0.4	119.1
	Composite	4.9	115.0	2.0	121.9
Wing 2, no ribs	Metal	3.4	72.5	0.4	76.3
	Composite	4.5	72.5	1.2	78.2
Wing 2, ribs	Metal	3.7	72.5	0.4	76.6
	Composite	4.75	72.5	2.0	79.25

Figure 13: Environmental Impacts in each life cycle phase for the 4 distinct wing configurations built in aluminium and composite, in *kiloparts*

4.4. Parametric Studies: COMSOL

It was assumed that the different materials used in the wing's production did not affect their aerodynamic behaviour. Thus, it was performed a parametric study regarding mixtures with distinct quantities of aluminium and composite and their structural behaviour. The wings tested were very complex structures and behaved as cantilevered beams, with a distributed pressure on their lower surface with positive Oz direction, as it was possible to understand from some of the vibration and buckling modes from the structural analysis in subsection 4.2. The 2 plies' thickness assumed different percentages of the total value and the top layer was made in composite and the lower layer in aluminium, in order to get a clearer comparison. In order to have the lowest tip displacement balanced with the lowest production cost, this simple model can represent a fast way to get this correlation. For that, different functions were created based on equation 4.

$$f(x) = w_1 \cdot f_1(x) + w_2 \cdot f_2(x), \tag{4}$$

in which $f(x)$ was the objective function, $f_1(x) = \frac{vector_{cost}}{cost_{max}}$, $f_2(x) = \frac{vector_{displacement}}{displacement_{max}}$, w_1 was the vector with the different weights applied to the cost dimensionless function and w_2 was the vector with the different weights applied to the displacement dimensionless function. 5 different functions were generated, as figure 14 exposes.

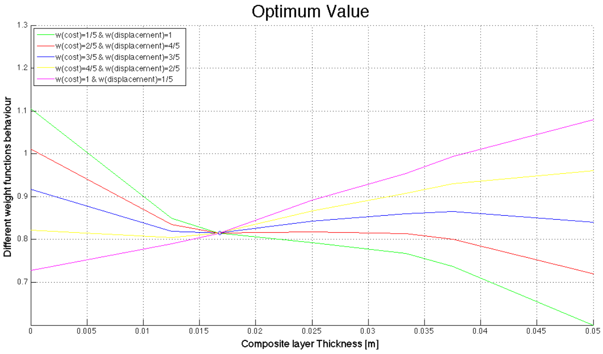


Figure 14: Optimum value for the parametric study

As it is possible to check from figure 14, the different functions intersect all in the same point. The x coordinate of that point gives a composite thickness of 16.822 mm and an aluminium thickness of 33.178 mm, which corresponds, respectively, to 33.64% of composite and 66.36% of aluminium. The main objective of this parametric study was to achieve the best correlation between the *Structural Analysis* and the *Production Cost Analysis* for a simplified body that has a similar behaviour as the wings tested. With this extra analysis performed besides the other ones, conclusions may be taken and solutions may be created in order to get the most suitable configuration for each aircraft company.

5. Conclusions

With the 3 different analyses the main goal of this thesis was achieved using an *Analytical Hierarchy Process* (*AHP*). It was considered that the aerodynamic behaviour, the structural response and the economic and environmental evaluations had the same importance (25%) in the classification of the different 12 wing configurations. Each wing was evaluated from 0 (worst) to 12 (best) in each of those 4 categories. Figure 15 presents the *AHP* performed to evaluate the distinct wing configurations.

Concept	PBCM	Aerodynamics (25%)	Structural (25%)	*LCC* (25%)	*LCA* (25%)	Total (100%)
Wing 1, no ribs	Metal	0.00	11.99	0.43	0.82	3.31
	ATL	0.00	11.23	0.05	0.49	2.94
	AFP	0.00	11.23	0.11	0.49	2.96
Wing 1, ribs	Metal	0.00	12.00	0.43	0.74	3.29
	ATL	0.00	11.25	0.00	0.00	2.81
	AFP	0.00	11.25	0.07	0.00	2.83
Wing 2, no ribs	Metal	12.00	5.64	12.00	12.00	10.41
	ATL	12.00	0.00	11.49	11.50	8.75
	AFP	12.00	0.00	11.66	11.50	8.79
Wing 2, ribs	Metal	12.00	5.68	11.99	11.92	10.40
	ATL	12.00	0.06	11.47	11.22	8.68
	AFP	12.00	0.06	11.65	11.22	8.73

Figure 15: Global evaluation of the 12 distinct wing configurations

From figure 15 the best wing out from out the 12 wing configurations was a high aspect ratio wing, without the introduction of ribs and manufactured in aluminium. This concept had the final highest score of 10.41 out of 12 possible. There are several key takeaways that must be taken out from this work:

- The increase of a wing's aspect ratio, for the same wing area, increases its $\frac{L}{D}$ factor;
- Wings with higher $\frac{L}{D}$ factor have better aerodynamic performance (since they allow to achieve the same lift with a smaller drag) and, consequently, consume smaller blocks of fuel during their useful life;
- Wings with higher aspect ratios have higher values of maximum tip displacement for the same load applied;
- The introduction of ribs in a wing's internal configuration decreases its maximum tip displacement providing extra structural resistance to the body;
- Not every composite configuration is suitable to this specific simulation model. It was expected a better structural response from the composite wings when compared to the aluminium ones and it did not happen due to the number of layers, fibre orientation and layers' thickness;
- For large bodies such as wings, the majority of their variable production costs (above 90% for metal and composite models) are material costs;
- In composites' production methods, the material cost is even higher since composite raw material is more expensive than aluminium;
- Composites' manufacturing processes are at about 8 times more expensive than metal processes, for this type of parts;
- Within the composites' manufacturing processes, for the same wing configuration, *ATL* model is more expensive than *AFP* model, due to the material waste;
- Composite wings' production has a higher environmental impact than aluminium wings since the energy used in their production phase is higher;
- The introduction of ribs in the wings internal structure also has a negative impact on the environment because the material quantity involved in the process is bigger;

- The actual scenarios for the composites' final disposal are not suitable in terms of environmental concerns. Therefore the options for metal's *EOL*, which include recycling material to other industries, are way ahead from composite's *EOL* destinations.

The major goal of the present work was achieved since insights on the design of a wing configuration were provided, considering aerodynamics, structures, costs and environmental impact. The pros and cons of each configuration were taken into account and this multidisciplinary project was successfully enrolled and concluded.

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